LASER FREQUENCY STABILIZATION USING A MOLECULAR BEAM

National Aeronautics and Space Administration

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Submitted by: Shaoul Ezekiel

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Massachusetts Institute of Technology
Research Laboratory of Electronics
Cambridge, Massachusetts 02139

SUMMARY OF RESEARCH

This report is a summary of the work done in a research program concerned with laser frequency stabilization using a molecular beam, that was partially sponsored by N. A. S. A. under Grant NGR 22-009-359 during the period February 1, 1969 - December 31, 1969.

The objective of this initial phase of the program was the investigation into the use of an iodine absorption resonance, observed in a molecular beam, as a long-term frequency reference for the stabilization of the 5145 Å Argon ion laser.

Briefly, the stabilization scheme is the following: A single-frequency 5145 Å laser beam excites the I_2 molecular beam at right angles and the absorption is measured by the induced resonance fluorescence of the I_2 molecules. This absorption resonance would then be used as a frequency reference in a feedback stabilization system. Shifts in the I_2 resonance frequency are negligible, because of the unperturbed and isolated conditions in the molecular beam. Since the molecular beam can be oriented at right angles to the laser beam, the width of the resonance line is limited to the observation width or, in this case, to the natural width, which is approximately 100 kHz, inferred from lifetime measurements.

In order to carry out the investigation, a short-term stable single-frequency Argon ion laser is essential, i. e., an Argon laser with a spectral width of less than a few kHz and a frequency drift of the order of 1 kHz/sec. Unlike the He-Ne and the CO_2-N_2-He lasers, the Argon ion laser short-term stability has not been adequately investigated. For our purposes, we were concerned with two sources of short-term instability: one was the fluctuation in the refractive index of the gain medium attributable, for example, to plasma oscillations and plasma noise in the discharge tube, and the other was the fluctuation in the physical length of the single longitudinal mode cavity comprising two cavities, a long one and a short one coupled together by means of a servo loop.

In the early part of the program several attempts were made, using existing equipment, to obtain a high-resolution I_2 absorption spectrum observed in a molecular beam that falls within the 5145 Å laser bandwidth. The data showed that the width of the individual I_2 resonance lines was of the order of 10 MHz which was much broader than the I_2 Doppler width of ~1 MHz because of the slit geometry in the molecular-beam apparatus. Because of the low density of I_2 molecules in the beam, the laser frequency must be scanned very slowly at ~1 MHz/sec to obtain an adequate signal-to-noise ratio in the induced fluorescence data. Clearly, the resolution of the observed I_2 spectrum was severely limited by the spectral width of the laser and the drift of the laser frequency during a scan period.

In order to study the frequency instability of the laser, an estimate of the laser spectral width had to be made independently from that obtained by observing the I_2 resonance width in the beam. A pressure-scanned, stable, Fabry-Perot cavity with a spectral width of ~1 MHz was designed and tested with a frequency stabilized He-Ne laser. Because of the rigidity of the cavity, lack of mirror adjustment, and the use of low expansion coefficient invar as the spacer, adequate stability was achieved for use in our study of the laser spectral width.

Also, the laser cavity itself was redesigned using four 1-in. diameter, invar rods, terminated by granite blocks. Several designs for a stable short (or Michelson) cavity were investigated and constructed. One particularly attractive design eliminated mirror adjustments.

At the same time, an investigation into techniques for the suppression of plasma oscillations in the Argon ion laser discharge tube was showing a great deal of progress and the remaining period under the N.A.S.A. grant was devoted to the study of these oscillations. The results of this work have been reported under "Investigations of Coherent Oscillations in an Argon-Ion Laser Plasma Tube," Applied Physics Letters, 1 January, 1971, and a reprint of this paper is attached to this report.

N. A. S. A. sponsorship, which was to continue for an additional three years, was withdrawn in January 1970, because of lack of funds resulting from the closing down of the N. A. S. A. Electronics Research Center in Cambridge, Massachusetts.

Publications and Theses

S. Ezekiel, "Laser Frequency Stabilization Using a Primary Frequency Reference," Proc. Twenty-third Annual Frequency Control Symposium, Atlantic City, N. J., May 1969.

T. J. Jach, "Laser-Saturated Iodine Absorption at 5145 Å," S. B. Thesis Department of Physics, M. I. T., May 1969.

A. J. Mazzella, "Investigation of Properties of a Spherical Mirror Fabry-Perot Interferometer and its Role in Laser Frequency Stabilization," S. B. Thesis, Department of Physics, M. I. T., June 1970.

D. C. Galehouse, U. Ingard, T. J. Ryan and S. Ezekiel, "Investigations of Coherent Oscillations in an Argon-Ion Laser Plasma Tube," Applied Physics Letters, Vol. 18, No. 1, pp. 13-15, 1 January 1971.

INVESTIGATIONS OF COHERENT OSCILLATIONS IN AN ARGON ION LASER PLASMA TUBE

D. C. Galehouse,* U. Ingard,* T. J. Ryan,† and S. Ezekiel†

Massachusetts Institute of Technology, Research Laboratory of Electronics, Cambridge, Massachusetts 02139

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Coherent fluctuations in the light of an argon ion laser have been investigated and laser operation free from these fluctuations has been achieved. Oscillations in the kHz range have been identified as anode oscillations and were suppressed by use of an auxiliary cathode. Oscillations related to the longitudinal magnetic field and to striations were eliminated by choice of plasma tube operating conditions. Wideband incoherent noise was less than 0.2%.

We report a method of suppression of low-frequency noise in an argon ion laser tube. We have found that the noise, which appears in the form of coherent fluctuations in the laser light, is a result of oscillations in the discharge in the vicinity of the anode (anode oscillations). The method of noise suppression then involves the use of an auxiliary cathode similar to that used by Pupp many years ago.[1]

This study was motivated by our need for the elimination of noise in the use of the argon ion laser in heterodyne spectroscopy of light scattered by ripplons,[2] and also by our efforts to frequency stabilize the 5145-Å laser line by using an iodine transition observed in a molecular beam as a frequency reference.[3,4]

Although several other investigators have been plagued by anode and other coherent oscillations in argon laser plasma tubes, the origin of these oscillations, usually in the range of several kHz to several hundred kHz, has not been established. Previous efforts to reduce the noise have involved a careful choice of operating parameters, such as gas pressure, discharge current, magnetic field, tube geometry, location of electrodes, etc. This has sometimes led to a relatively "quiet" operation of the laser.

The discharge tube used in our study was made of quartz with the anode and cathode mounted at right angles to the tube axis. An auxiliary cathode was mounted within a cylindrical molybdenum anode, as shown in Fig. 1. The bore diameter of the plasma tube was 3 mm and the length of the active gain region was 40 cm. In this arrangement, two independent discharges can be run simultaneously, one between the anode and the main cathode, and the other one between the anode and the auxiliary cathode. The power supplies were filtered but not regulated.

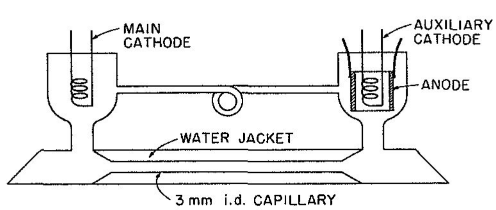

FIG. 1. Schematic diagram of argon ion laser discharge tube with auxiliary cathode.

With the auxiliary discharge turned off, strong coherent fluctuations in the laser light were observed. An oscilloscope picture of the corresponding output signal from a photodetector is shown in Fig. 2, together with the frequency spectrum obtained from a spectrum analyzer. The main discharge current was 15 A, the gas pressure was 350 μm, and the axial magnetic field was 350 G. The fundamental frequency was found to be independent of the main discharge current but linearly

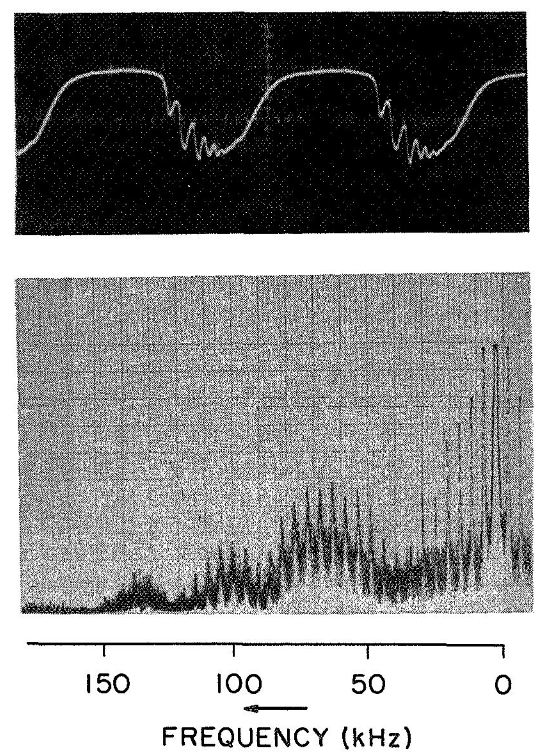

FIG. 2. Fluctuation in the laser light caused by anode oscillations in the argon ion discharge tube. Upper: an oscilloscope picture of the fluctuations. Time scale 0.2 msec/cm. Lower: corresponding frequency spectrum obtained from a spectrum analyzer. (Main discharge current 15 A, argon pressure 350 μm, axial magnetic field 350 G.)

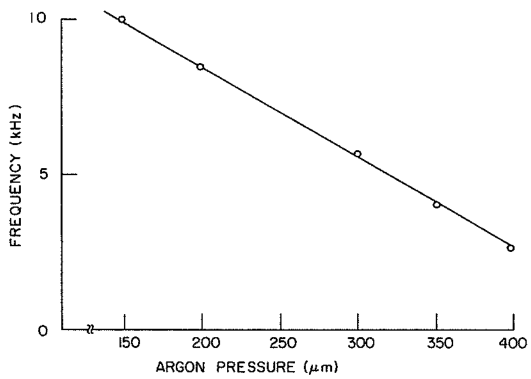

FIG. 3. Fundamental frequency of anode oscillation as a function of argon pressure. (Argon pressure was measured on a thermocouple gauge, calibrated for air.)

dependent on gas pressure, at least over a limited range, as shown in Fig. 3.

With the auxiliary discharge turned on, and the current adjusted to a value above 2.5 A, the coherent noise spectrum in Fig. 2 was completely eliminated. This occurred in the entire range of available discharge currents up to 20 A and magnetic fields up to 650 G in the important pressure range 200–400 μm. In this region the laser light was free from any coherent oscillations in the frequency range of the photodetector response, which was approximately 10 MHz.

Although this noise suppression represents our main result, we wish to mention that our noise studies have also resulted in identification of other oscillations. For example, at axial magnetic fields exceeding a threshold value that depends on the gas pressure, we have observed coherent narrow-band oscillations in the 100-kHz range which appear to be related to the Kadomtsev instability.[5] The frequency increased with the discharge current, as shown in Fig. 4, but was found to be independent of the magnetic field (above its threshold value), at least in the range of magnetic fields (< 750 G) available in our experiment. The threshold value of the magnetic field was found to decrease with pressure. For example, at an argon pressure of 200 μm the critical magnetic field was 650 G, whereas at 150 μm it was 250 G. Because of limitations in our magnetic field power supply we were not able to determine the critical magnetic field at pressures above 200 μm.

At gas pressures below 100 μm, other oscillations were observed, probably related to striations. Striations are known to occur only below a certain pressure-dependent critical value of the discharge current.[6] At the discharge currents used in our experiment the conditions for occurrence of striations were satisfied only for pressures below 100 μm.

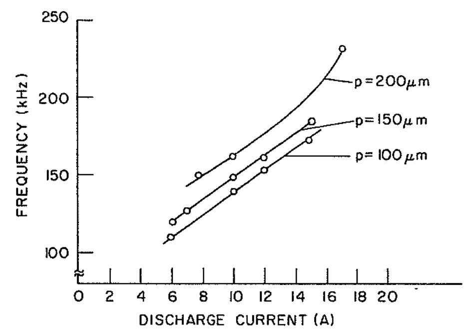

FIG. 4. Oscillation frequency of Kadomtsev-related instability as a function of discharge current and argon pressure.

These oscillations were unaffected by the auxiliary discharge and the magnetic field.

In addition to the coherent oscillations described above, we have detected wideband incoherent background noise in the laser light. The amplitude of the noise depended on the argon pressure and always decreased with increasing discharge current. At a pressure of 300 μm, a discharge current of 15 A, and a magnetic field of 350 G, the peak-to-peak noise in a bandwidth of 10 Hz-10 MHz was less than 0.2% of the laser light.

A more extensive discussion of the various types of oscillations and their dependence on various parameters will be published elsewhere. This will also include questions not mentioned in this letter, such as the influence of the external circuit components on the various types of oscillations and the possible use of these oscillations in plasma diagnostics.

In conclusion, then, we can say that for the discharge tube configuration utilized, the use of an auxiliary or secondary discharge between an auxiliary cathode and the anode makes it possible to obtain a laser operation free from coherent oscillations over a range of useful operating conditions. This range, in our case, for low values of the axial magnetic field, say, less than 650 G, corresponds to argon pressures between 200 and 400 μ independent of discharge current.

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*Dept. of Physics.
†Dept. of Aeronautics and Astronautics.

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